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AN EXAMINATION OF THE CHANGE IN THE EARTH'S ROTATION RATE FROM ANCIENT CHINESE OBSERVATIONS OF LUNAR OCCULTATIONS OF THE PLANETS

JAMES L. HILTON AND P. K. SEIDELMANN
U.S. Naval Observatory, 3450 Massachusetts Ave. NW, Washington, DC 20392

LIU CIYUAN
Shaanxi Astronomical Observatory, Lintong, Shaanxi, China
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ABSTRACT

A study is made of fifty-eight records of naked eye observations of occultations of the planets by the Moon chosen from the Chinese dynastic histories. These records cover the period from 68 B.C. to 575 A.D. Fifty-three of these records fall in the time period between 100 A.D. and 575 A.D., a period with no other known observations useful for Earth rotation studies. The observations are compared to topocentric ephemerides computed using Bretagnon's planetary theories VSOP82 and the Chapront-Touze lunar theory ELP2000-85. The area of the Earth from which an individual lunar occultation is observable is too large to produce a useful value of the acceleration parameter, C ($Ct^2 = \mathrm{ET} - \mathrm{UT}$), from untimed occultation records. However, the entire series of observation records produces a weak estimate for the value of C (12.6 s cy^{-2} to 35.7 s cy^{-2}). The uncertainty in C is difficult to estimate. Overall, the check on the change in the rotation rate is very weak, but it represents the limit of what can be done with known, untimed occultation records.

1. INTRODUCTION

Stephenson & Morrison (1984) found an average value for C, the accumulated difference between ephemeris time (ET) and universal time (UT), of 28.3 s cy^{-2}, from solar eclipses in ancient Babylonian and medieval Arabian records. However, eclipse records are available for only a small portion of the historical time period. One large gap in the historical record extends from 100 to 800 A.D.

The Chinese records of lunar occultations of planets offer an independent check of C. Many of the Chinese occultation observations also cover the 100 A.D.–800 gap. Liu has culled from the official Chinese dynastic histories 165 records of planets being occulted by the Moon. These occultations cover the time period from February 69 B.C. (JD 1696265) through May 1638 A.D. (JD 2319475), including 72 observations between 100 and 800 A.D. Many of the records are unclear, so an easily interpreted subset of 58 records used by Liu (1988) was selected for study. These records cover the period from 69 B.C. (JD 1696265) through 575 A.D. (JD 1931078), and include 53 observations between 100 and 575 A.D. The place of each observation was the capital of the contemporary dynasty (see Table 1). The data set includes observations made at seven different capitals, including pairs of observations for eight occultations observed separately by rival Chinese dynasties.

2. THE EPHEMERIDES OF THE RECORDED OBSERVATIONS

Analysis was performed using a program to determine the apparent position of a planet relative to the Moon and the apparent angular radius of the Moon. Most of the programing was done using apparent place routines developed by Kaplan (1988). The positions of the planets were determined using the planetary theories VSOP82 by Bretagnon (1982), and the positions of the Moon were determined using the Chapront-Touze & Chapront (1988) lunar theory (ELP2000-85) for historical periods. The angular acceleration of the Moon used was $-23''.895$ cy^{-2} (Dickey *et al.* 1982).

Ephemerides were produced for each of the recorded observations using a time step of 0.001 day. The ephemerides for each event are calculated for three values of C (25.5, 32.0, and 66.8 s cy^{-2}). Table 2 shows the results for the case $C = 25.5$ s cy^{-2}. The least separations given in Table 2 are the center-to-center separation between the Moon and the occulted planet. A negative value for the least separation means that the planet passed to the south of the Moon's center. If the planet was not actually occulted by the Moon, the beginning time in column 7 is the time of closest approach.

None of the test values for the acceleration parameter, C, produces a model in which all of the planets were occulted for all of the records given in Table 2. For some of

TABLE 1. The names and positions of the Chinese capitals.

No.	Name	Longitude	Latitude	Altitude
1	Xian	108°9 E	34°2 N	350 m
2	Loyang	112°4 E	34°7 N	200 m
3	Xuchang	113°8 E	34°0 N	50 m
4	Nanjing	118°8 E	32°0 N	50 m
5	Datong	113°2 E	40°1 N	1250 m
6	Wuwei	102°6 E	37°9 N	1500 m
7	Linzhang	114°6 E	36°3N	50 m

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TABLE 2. Calculated Ephemerides of Chinese occultation observations.

No.	Julian Date (Recorded)	Planet	Capital	Lunar Rad.(′)	Elong. Moon(°)	Begin (Date)	End (Date)	Min. Sep. (′)	Alt. Sun (°)	Alt.Moon (°)	Mag. Planet	Notes
1	1696265	Mars	1	16.46	-127	.161	.197	9.581	-64.3	15.2	-0.96	
2	1711202	Saturn	1	16.38	167	.271	.319	3.097	-63.4	52.4	-0.24	
3	1743015	Mars	2	15.19	-98	.276	.334	1.177	-58.1	20.9	-0.35	
4	1747692	Venus	2	14.86	45	.000	.046	-3.439	-31.5	5.5	-5.38	a
5	1801710	Mars	3	15.79	115	9.875	9.928	4.201	8.5	21.7	-1.44	c
6	1844752	Venus	4	16.64	-40	.568	.612	-10.696	48.8	73.8	-6.95	
7	1845342	Venus	4	15.02	41	.497	.547	9.599	19.1	39.6	-6.83	
8	1850706	Saturn	4	16.85	-178	.251	.290	-10.181	-63.7	64.7	-0.33	
9	1851809	Jupiter	4	16.19	-51	.364	.407	5.751	-30.2	-7.5	-1.89	
10	1852991	Venus	4	16.50	45	.552	.600	-10.999	36.7	41.4	-5.36	
11	1853973	Venus	4	14.73	46	2.997	3.028	-11.490	-35.3	3.3	-5.53	a
12	1854421	Jupiter	4	15.53	101	.185	.212	11.586	-69.9	16.6	-2.36	
13	1854803	Mars	4	14.86	82	.342		-30.417	-31.4	-30.0	0.40	
14	1862485	Mars	4	14.88	139	.256		-29.918	-49.3	29.8	-1.10	
15	1863155	Mercury	4	15.44	15	4.914	4.931	-14.349	-5.8	7.6	-2.52	
16	1864652	Mars	4	15.81	-82	.270	.314	-7.362	-53.9	8.7	-0.02	
17	1865116	Jupiter	4	16.59	168	.238	.286	1.570	-30.9	27.7	-2.64	
18	1866257	Venus	4	15.17	45	.034	.074	0.577	-17.8	8.9	-6.04	a
19	1866272	Jupiter	4	15.70	139	.028	.062	-7.074	-18.3	-6.0	-2.82	b
20	1867482	Jupiter	4	15.81	-149	.301	.328	-13.998	-44.9	74.1	-2.61	
21	1868028	Mercury	4	14.72	24	.042		-17.831	-22.2	-1.4	-2.58	
22	1868028	Mercury	5	14.79	24	.039		-21.216	-13.0	6.8	-2.58	
23	1868691	Jupiter	4	15.08	-172	.210	.264	4.756	-58.4	58.7	-2.49	
24	1868691	Jupiter	5	15.21	-172	.195	.249	3.408	-52.0	50.2	-2.49	
25	1869222	Saturn	4	16.53	175	1.942		-28.603	-0.5	-4.4	0.50	
26	1869222	Saturn	5	16.52	175	1.948		-32.046	3.4	-8.0	0.50	
27	1869304	Saturn	4	16.22	99	3.997		-21.523	-35.1	43.1	0.75	
28	1869304	Saturn	5	16.20	99	3.995		-29.713	-30.6	36.5	0.75	
29	1869713	Venus	4	15.33	42	2.942	2.990	4.061	-16.4	21.4	-5.05	
30	1869713	Venus	5	15.14	42	2.940	2.988	-5.002	-14.5	19.8	-5.05	
31	1871795	Mars	5	15.37	-118	.167	.196	12.067	-44.5	19.8	-1.47	
32	1873715	Saturn	4	16.50	-118	.295	.343	8.921	-50.1	63.7	0.66	
33	1874867	Mars	5	15.71	-122	.324		16.653	-42.8	44.1	-0.80	
34	1876692	Jupiter	4	16.53	168	1.996		18.992	-26.6	38.8	-2.52	
35	1876692	Jupiter	5	16.71	167	1.977	2.012	9.807	-17.5	29.5	-2.52	
36	1881045	Venus	5	16.47	-41	.441	.476	-11.934	-14.8	15.4	-4.96	
37	1881630	Saturn	5	16.00	-100	.179		-21.477	-36.0	17.2	-0.17	
38	1894641	Saturn	5	14.93	104	.184		15.570	-45.1	28.3	0.12	
39	1899987	Mars	4	14.64	115	6.841	6.890	-7.969	9.9	27.5	-1.20	
40	1900749	Jupiter	4	16.56	46	8.975	9.013	7.136	-27.3	14.4	-2.16	
41	1901050	Saturn	4	16.38	112	.074		-37.230	-53.1	32.2	0.57	
42	1901050	Saturn	5	16.36	112	.067		-45.179	-43.8	28.0	0.57	
43	1902448	Saturn	2	15.50	-127	.278	.326	7.963	-32.8	54.7	-0.05	
44	1904803	Saturn	2	15.76	149	.225	.261	-10.378	-71.8	51.8	-0.25	
45	1904878	Venus	2	16.47	22	.420	.457	4.917	-0.4	14.5	-7.61	d
46	1904994	Venus	2	15.67	-38	.258	.295	-0.439	-33.3	-6.1	-4.79	b
47	1908583	Saturn	2	14.83	150	.178	.235	-1.469	-32.8	35.1	0.19	
48	1908665	Saturn	2	14.90	71	.078	.119	-5.851	-30.4	5.7	0.45	a
49	1911794	Venus	6	16.45	45	.031	.071	7.864	-24.2	20.4	-5.74	
50	1912342	Mars	2	15.74	-111	.238	.276	-11.058	-49.0	46.0	-1.18	
51	1913431	Saturn	2	15.27	-144	.372		19.303	-15.8	48.7	-0.18	
52	1913595	Saturn	2	15.52	48	.032		-40.592	-30.0	16.4	0.16	
53	1914672	Mars	2	15.19	-141	.207		27.876	-71.6	46.6	-1.03	
54	1914699	Mars	2	14.87	-174	8.929	8.963	-5.821	1.4	-5.1	-1.43	b, c
55	1921865	Jupiter	4	14.91	65	4.957	5.009	6.036	-17.8	22.9	-2.17	
56	1921865	Jupiter	7	14.87	65	4.948	5.004	2.605	-12.4	22.9	-2.17	
57	1928575	Jupiter	4	16.65	138	.236	.276	0.908	-60.2	35.4	-2.45	
58	1931078	Venus	1	15.57	46	7.882	7.936	6.109	6.6	42.0	-6.14	c

Notes:

A negative sign for least separation indicates that the planet passed to the south of the Moon's center while a positive least separation indicates that th Moon's center.

a. Moon set during occultation.
b. Moon rose during occultation.
c. Sun set during occultation.
d. Sun rose during occultation.

TABLE 3. The value of C as a function of weighting scheme.

Weighting Scheme	Relative weights (Planet)					C	Stability	Std. Dev.
	Mercury	Venus	Mars	Jupiter	Saturn	(s cy^{-2})	(s cy^{-2})	(s cy^{-2})
Equally Weighted	1.0	1.0	1.0	1.0	1.0	12.6	0.6	10.2
Mean Luminosity	0.19	10.00	0.12	1.79	0.16	35.6	3.3	23.9
Luminosity	.09-.10	.74-10.0	.006-.04	.333-1.21	.005-.013	35.7	1.6	19.1
Bright Planets Only	0.0	1.0	0.0	1.0	0.0	35.1	5.3	31.1

TABLE 4. The acceleration parameter for different time periods.

Time Period	No. of Occultations	Acceleration Parameter ($s\ cy^{-2}$)	Stability ($s\ cy^{-2}$)
301-400	15	42.9	18.2
401-500	23	32.4	14.2
501-600	15	41.6	12.6

the recorded events no reasonable value of C will produce an occultation.

3. DETERMINATION OF THE ACCELERATION PARAMETER, C

For a total eclipse of the Sun, the path of totality is, at most, only about 210 km wide which corresponds to a minimum uncertainty in ΔT of 7.5 min at the equator (210 km/40075 km$\times$1440 min) for an untimed observation. The mean width of the path of an occultation by the Moon over the Earth's surface, however, is closer to 3520 km. Thus, the minimum uncertainty in ΔT from a single occultation is 2.1 hr at the equator. The uncertainty in the path of the occultation over the surface of the Earth can be reduced if information such as the occultation occurred near sunrise, sunset, moonrise, or moonset is available.

A value for C was determined by minimizing the sum of the squares of the least separations as a function of C. Four different schemes for weighting the observations were used. These weighting schemes are: (1) all observations equally weighted, (2) observations weighted by the mean apparent luminosity of the occulted planet, (3) weighting each observation by the calculated apparent luminosity of the occulted planet at the time of occultation, and (4) giving the bright planets (Venus and Jupiter) equal weight and the dim planets (Mercury, Mars, and Saturn) zero weight. After a value for C was determined, the least separation from the empirical quadratic function was compared with the value from the ephemeris to check for correctness. The four estimates for C are given in Table 3. Both of the luminosity weighted estimates and the Venus and Jupiter only estimate cluster around 35.5 s cy^{-2}, while the equally weighted estimate is significantly different at 12.6 s cy^{-2}.

Three methods of testing the uncertainty in the solutions for C were made. The first method was to compute the standard deviation in C. The second test was made on the stability of the solution by the exclusion of individual observations. This estimate was made by going systematically through the data and determining the change in the value of C caused by the removal of a single observation. The third test was to determine the values of C for different eras in the data by splitting it into three subsets in time and comparing the values for C. The results for this test are given in Table 4.

Overall, the 58 observations analyzed here represent a very weak check of the value of the acceleration parameter. However, aside from the equal weighting case, all of the estimates for C are in amazingly good agreement with the values of C determined from other ancient observations. The observations here are also useful because they cover a historical period with no other known useful observations.

4. CONCLUSIONS

Historical records of occultations of planets by the Moon provide an estimate of the value for the acceleration parameter, C, that is consistent with the values provided by other methods of determining the acceleration parameter. However, the uncertainty in the value is large.

A global solution of all data may give a better result. Another source of improvement might be made by including ancient Chinese records of occultations of stars and planets by the planets in Hilton *et al.* (1988). However, even including all 107 observations will still produce a standard deviation on the order of 13–18 s cy^{-2}. Hence the use of untimed occultations produce only very poor estimates of C.

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